

# **Thermospheric/Ionospheric Extension of the Whole Atmosphere Community Climate Model**

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## **LONG-TERM GOALS**

A primary goal of this project is to develop a model that encompasses the entire atmosphere, from the ground/ocean to the upper thermosphere, by extending the Whole Atmosphere Community Climate Model (WACCM) upward, making use of the physics and many of the algorithms of the National Center for Atmospheric Research Thermosphere-Ionosphere-Mesosphere-Electrodynamics General-Circulation Model (NCAR TIME-GCM). Such a seamless whole atmosphere model will enable us to self-consistently study how elements in the coupled upper atmosphere/ionosphere system interact with one another and to determine how this coupled system responds to the variable energy input from the sun and the complex interactions between the lower atmosphere/ocean and the middle and upper atmosphere. The information from this research will be useful for ONR to develop a seamless operational model that simulates the present day structure and dynamics of the thermosphere-ionosphere-mesosphere-lower atmosphere-system including its response to solar variability and global change.

## **OBJECTIVES**

Our scientific objectives are to study the nature of the sources of variability in the upper atmosphere/ionosphere system self-consistently using a seamless model spanning the whole atmosphere. The primary technical objectives of the current work are: (1) Extend the upward boundary of the WACCM to the top of the thermosphere ( $3 \times 10^{-9}$  hPa, around 500~km) by including the main thermospheric and ionospheric processes. (2) Test and refine the extended WACCM by comparison with empirical models and with observations of upper atmospheric tides, ionospheric electric fields, and geomagnetic perturbations. (3) Help the development of NOGAPS-ALPHA into the lower thermosphere by transferring appropriate packages from WACCM. (4) Help the development of ionospheric data assimilation schemes at the Utah State University by providing WACCM output with tidal and planetary wave variability.

## **APPROACH**

The extended WACCM is built upon the WACCM version 3 (WACCM3), which is based on the NCAR Community Atmospheric Model (CAM3), and includes all the physical parameterizations of

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that model. There are three dynamical cores available in CAM3, and the finite volume dynamical core [Lin, 2004] has been used for WACCM3. This method is superior for mass conservation and important for the interactive chemistry in WACCM3. The WACCM3 chemistry module is derived from the three-dimensional chemical transport Model for Ozone and Related chemical Tracers (MOZART) [Brasseur *et al.*, 1998], which solves 51 neutral species plus 5 major ion species ( $O_2^+$ ,  $O^+$ ,  $NO^+$ ,  $N^+$ , and  $N_2^+$ ) and electron. Processes important for the energetics in the upper atmosphere, including photolysis in the solar spectral range from the EUV to 750 nm, photoionization, solar heating at short and long wavelength, including infrared transfer under non-local thermodynamic equilibrium (NLTE) conditions, auroral processes, ion drag, and Joule heating are calculated or parameterized in WACCM3. Gravity wave forcing and eddy diffusion induced by gravity wave breaking are parameterized in WACCM3. Molecular diffusion of minor species diffusion in the vertical direction is also calculated. A detailed summary of WACCM3 can be found in Garcia *et al.* [2007].

The present upper boundary of WACCM, at around 150~km, only permits studies of the thermosphere up to about 110-120~km, because higher altitudes are significantly affected by the assumed upper boundary conditions. The first phase of this development is to raise the upper boundary to the model to the upper thermosphere and at the same time include the physics that is relevant for the thermosphere. In particular, major species diffusion and species dependent molecular weight, specific heats, and gas constants need to be formulated in WACCM3, and upper boundary conditions for winds, temperature, and various species appropriate for the upper thermosphere need to be implemented. With these developments, WACCM now has a thermospheric component. The WACCM thermospheric structures is being validated against empirical model results and TIME-GCM results.

At the same time, we have further developed the NCAR thermosphere-ionosphere-mesosphere-electrodynamics general circulation model (TIME-GCM) and continued to use the model for studying the upper atmospheric variability. To better resolve the impact of lower atmospheric variability on the upper atmosphere and to take advantage of the augmented computing power afforded by the new NCAR facilities, the spatial resolution of TIME-GCM has been doubled in each dimension, and the lower boundary condition of TIME-GCM can now be specified by assimilated data from the European Centre for Medium-Range Weather Forecast (ECMWF), which has 6-hourly output.

NCAR personnel participating in this work include: Han-Li Liu (dynamics of the middle and upper atmosphere), Raymond Roble (aeronomy and global upper atmosphere and ionospheric dynamics), Arthur Richmond (electrodynamics and upper atmosphere waves), Stanley Solomon (ionospheric physics), Astrid Maute (scientific support on ionospheric physics), Liying Qian (scientific support on thermospheric physics), Joseph McInerney (scientific/programming support: model upward extension), Benjamin Foster (programming support and model development). WACCM is a collaborative effort between three NCAR Divisions: The High Altitude Observatory (HAO), The Climate and Global Dynamics Division (CGD), and the Atmospheric Chemistry Division (ACD), and involves scientists from these divisions as well as outside collaborators.

## WORK COMPLETED

Extended the WACCM ( $1.9^\circ \times 2.5^\circ$  degrees horizontal resolution) to the upper thermosphere at  $3.4 \times 10^{-9}$  hPa (the same as the upper boundary of the TIME-GCM, approximately at 500 km). In the process of achieving this upward extension, we have (1) Implemented modules to resolve the major species diffusion, which becomes increasingly important above 110 km. (2) Implemented modules and revised

the codes to reflect the constituent-dependency of the specific heats, gas constant, and mean molecular weight. They were set to constants in the previous codes. (3) Revised the treatment of the vertical diffusion equations for minor species and heat conduction equation.

Made test runs using the extended WACCM over one model year under solar medium condition, and obtained the wind structure, thermal structure, the vertical profiles of major species (N<sub>2</sub>, O<sub>2</sub>, O), oxygen species (O<sub>3</sub>, O<sub>1</sub>D, O<sub>2</sub>\_1S, O<sub>2</sub>\_1D), hydrogen species (H, H<sub>2</sub>O, HO<sub>2</sub>, OH), nitrogen species (NO, NO<sub>2</sub>), carbon species (CO, CO<sub>2</sub>, CH<sub>4</sub>), ions (O<sup>+</sup>, O<sub>2</sub><sup>+</sup>, NO<sup>+</sup>, N<sup>+</sup>, N<sub>2</sub><sup>+</sup>) and electron density from the ground to the upper thermosphere.

Made initial comparisons with TIME-GCM and the wind/temperature/compositional structures in the middle and upper atmosphere are in good agreement with those obtained from TIME-GCM. This is the first time that the wind, temperature and compositional structures are resolved from the ground to the upper thermosphere self-consistently in a seamless model.

Developed and tested a high resolution version of TIME-GCM (2.5°x2.5°x0.25 scale height) with the lower boundary specified by the ECMWF operational model results at 10 hPa (2.5°x2.5° and 6-hourly output). Initial simulation shows that the tidal variability and non-migration tides are better resolved.

Further development of TGCM/WACCM postprocessors: (1) Further developed the TGCM IDL postprocessor so that it can process results from the extended WACCM simulations. (2) Further developed the TGCM FORTRAN postprocessor so that it can process results from the high resolution version of TIME-GCM.

Provided the Naval Research Laboratory Navy Operational Global Atmospheric Prediction System Advanced Level Physics-High Altitude (NRL NOGAPS-ALPHA) team with an upgraded version of the Global Mean Model and the WACCM FUV module.

Provided the Utah State University Global Assimilation of Ionospheric Measurements (USU GAIM) team with WACCM output for studying ionospheric data assimilation in the presence of variability due to lower atmosphere perturbations (tides, planetary waves, and gravity waves).

## RESULTS

Figure 1 shows the globally averaged number density of major species, oxygen, hydrogen, nitrogen, carbon compounds, and major ion species plus electrons, and zonally averaged zonal wind, meridional wind, and temperature under December solstice condition from the extended WACCM simulation. The compositional structures in the upper atmosphere compare well with those derived from the global mean model. The number densities of the ion species and electron decrease faster above their peak values compared to the global mean model results, likely due to the absence of ambipolar diffusion in the model. The zonal jet and jet reversals in the troposphere, stratosphere, mesosphere and thermosphere and the strong meridional circulations in the mesosphere and thermosphere are in reasonable agreement with climatology. The temperature structure, including the cold summer mesopause driven by gravity waves, is also reasonably reproduced in the whole atmosphere. Figure 2 shows the meridional wind at a specific location (46°S and longitude 0) as a function of time and height. Multiple-day oscillations in the troposphere/stratosphere, quasi-two-day waves in the

mesosphere, and strong tides in the mesosphere and thermosphere are evident in the plot. The tides also display clear short-term variabilities.

The one-year simulation using the extended WACCM shows a semi-annual variation in thermospheric density and the O/N<sub>2</sub> ratio. Figure 3 shows the globally averaged O/N<sub>2</sub> at  $1.8 \times 10^{-5}$  Pa (approximately 250 km) over the one-year simulation. The model result displays O/N<sub>2</sub> peaks around the two equinoxes and minimums at the solstices. The phase and the magnitude of the semi-annual variation are in good agreement with MSIS results at a similar pressure level. On the other hand, the O/N<sub>2</sub> at the lower thermosphere (120 km) does not have a clear semi-annual variation, which indicates that the semi-annual variation in the middle/upper thermosphere is likely determined by the thermospheric circulation rather than the density or flux of O in the lower thermosphere.

Using simulation results from WACCM, Liu et al. revisit the wind balance in the mesosphere and lower thermosphere and demonstrate geostrophic balance approximate holds in the meridional direction but no longer valid in the zonal direction due to the large zonal gravity wave forcing. As a result, the zonal mean geostrophic meridional wind is significantly different from the actual zonal mean meridional wind, and the residual mean meridional circulation derived from geostrophic winds is much weaker than that derived from model winds. The ageostrophic contribution comes primarily from gravity wave forcing, so that there is an approximate three-way balance between pressure gradient, Coriolis force, and gravity wave forcing. The relationship between the geostrophic winds and actual winds is also tested using measurements from TIMED SABER and TIDI instruments. This research provides a possible route to directly infer gravity wave forcing from meridional wind measurements. (H.-L. Liu, D. R. Marsh, Q. Wu, and J. Xu, Wind balance in the mesosphere and lower thermosphere, in preparation).

Yuan et al. used multiple years of continuous observations of mesopause temperature and horizontal wind, each lasting longer than 24 hours, from Colorado State University Na Lidar Facility Fort Collins, CO (41°N, 105°W) to derive monthly climatology and seasonal variations of temperature and horizontal winds. The observed mean-state in temperature, zonal and meridional winds are compared with the predictions of 3 current general circulation models: WACCM3, the Hamburg Model of the Neutral and Ionized Atmosphere (HAMMONIA), and the year 2003 simulation of the TIME-GCM. While general agreement is found between observation and model predictions, there exist discrepancies between model prediction and observation, as well as among predictions from different models. The altitude of winter zonal wind reversal and seasonal asymmetry of the pole-to-pole meridional flow are also compared, with the importance of full-diurnal-cycle observation for the determination of mean states studied. (T. Yuan, C.-Y. She, D. A. Krueger, F. Sassi, R. R. Garcia, R. G. Roble, H.-L. Liu, and H. Schmidt, Climatology of mesopause region temperature, zonal wind and meridional wind over Fort Collins, CO (41°N, 105°W) and comparison with model simulations, *J. Geophys. Res.*, in press, 2007).

Marsh et al. used WACCM3 to study the atmospheric response from the surface to the lower thermosphere to changes in solar and geomagnetic forcing over the 11-year solar cycle. Energy inputs include solar radiation and energetic particles, which vary significantly over the solar cycle. This paper presents a comparison of simulations for solar cycle maximum and solar cycle minimum conditions. Changes in composition and dynamical variables are clearly seen in the middle and upper atmosphere, and these in turn affect the terms in the energy budget. Generally good agreement is found between the model response and that derived from satellite observations. A small but statistically significant

response is predicted in tropospheric winds and temperatures which is consistent with signal observed in reanalysis data sets. (Marsh, D. R., R. R. Garcia, D. E. Kinnison, B. A. Boville, K. Matthes, F. Sassi, and S. C. Solomon. Modeling the whole atmosphere response to solar cycle changes in radiative and geomagnetic forcing. *J. Geophys. Res.*, *in press*, 2007.)

Liu studied the large wind shear and fast transport above the mesopause and possible relationship with gravity waves and tides. With the maximum atmospheric static stability above the mesopause, large wind shears can be obtained under the limit of dynamic stability and the consistently large observed wind shears there can thus be related to the stability constraint set by the background atmosphere. The maximum wind shears determined from this stability limit are found to be in general agreement with the outer envelope of most of the large wind shears from chemical release experiments at low and mid-latitudes. Diagnostic calculations also indicate that the meridional transport in this region may not be well understood solely by examining the mean meridional circulation, and large amplitude tides/planetary waves can play an important role in the bulk transport of tracers. Strong stochastic winds, presumably due to gravity waves, do not seem to significantly change the large scale pattern of the transport but may extend the range of the tracer movement. (Liu, H.-L., On the large wind shear and fast meridional transport above the mesopause, *Geophys. Res. Lett.*, 34, L08815, doi:10.1029/2006GL028789, 2007.)

Liu et al. studied the large mesospheric temperature inversion and coincident strong short-term tidal variability using temperature and wind measurements from lidar, NASA TIMED/SABER and TIDI instruments and compare these results with TIME-GCM. With a large transient planetary wave specified at the model lower boundary, the model is able to produce strong diurnal tidal variability comparable to that from the lidar observation, and the modeled temperature inversion is similar to that from the SABER measurement. The model results suggest that the planetary/tidal wave interaction excites non-migrating tides and modulates the gravity modes and/or the rotational modes of the diurnal migrating tide. Among the non-migrating tides, the diurnal zonally symmetric ( $S=0$ ) component is the strongest, and its interaction with the planetary wave leads to a strong diurnal eastward wavenumber 1 component. (Liu, H.-L., T. Li, C.-Y. She, J. Oberheide, Q. Wu, M. E. Hagan, J. Xu, R. G. Roble, M. G. Mlynczak, J. M. Russell III, Comparative study of short term tidal variability, *J. Geophys. Res.*, 112, doi:10.1029/2007JD008542, 2007.)

## IMPACT/APPLICATIONS

Both WACCM and TIME-GCM are community models and the development, evaluation and application of these models have and still will have extensive community involvement. We participate in NRL studies, NSF Coupling and Energetics of Atmospheric Regions (CEDAR), and Space Weather Initiative (SWI) programs. We worked closely with NASA TIMED team to help interpreting the observational results, and a NASA Small Explorer team for mission planning. The WACCM provides a seamless modeling tool to study whole atmosphere coupling and connecting the tropospheric climate with space weather, and it attracts participation from the lower, middle and upper atmosphere communities. We also participate in the NCAR Climate Systems Modeling effort in examining the couplings between the upper and lower atmospheres and in an attempt to understand the effects of the variable solar outputs on the coupled Earth system. We also work closely with other seamless modeling teams, such as the NRL NOGAPS-ALPHA team.

## RELATED PROJECTS

The numerical modeling effort is complemented by a data analysis and interpretation efforts, and comparative studies with observations and other model development. We have actively participated or have participation from the following projects/missions:

NASA TIMED Satellite Mission.

NSF CEDAR: Whole-Atmosphere Modeling of the Thermosphere/Ionosphere Responses to Lower-Atmosphere Dynamics and Variability.

NSF Lidar Consortium.

NCAR Community Climate System Model.

NRL NOGAPS-ALPHA.

USU GAIM.

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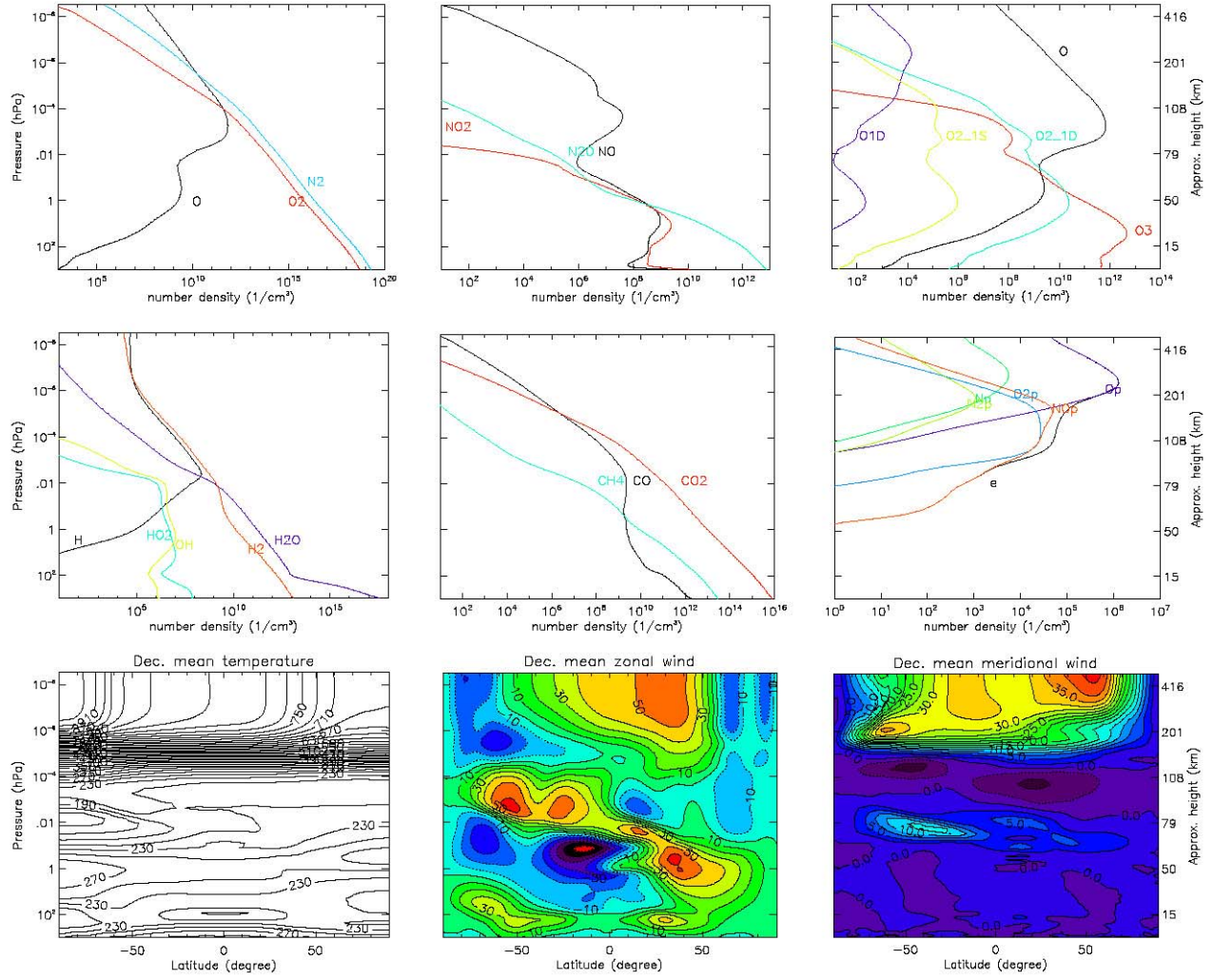
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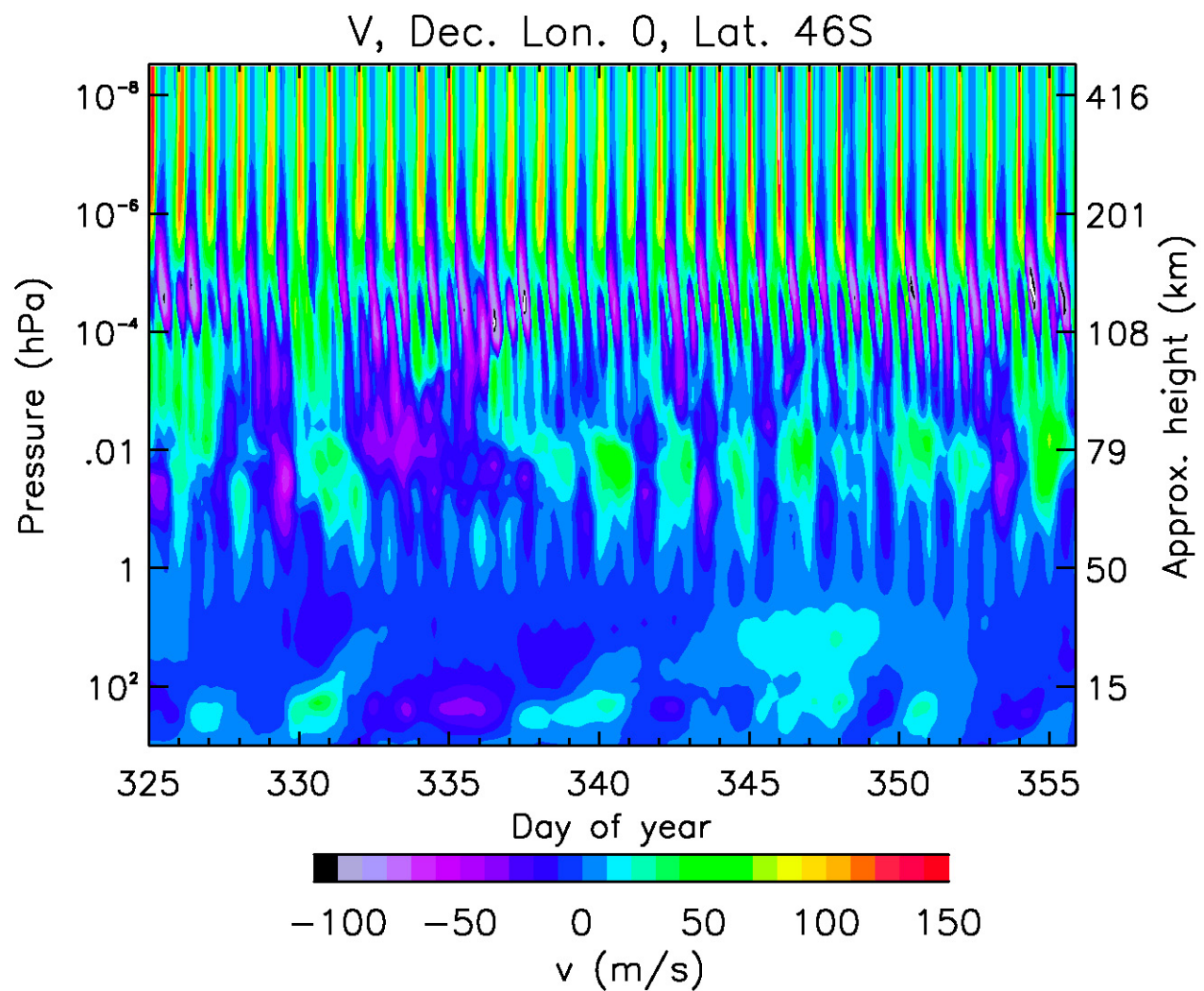
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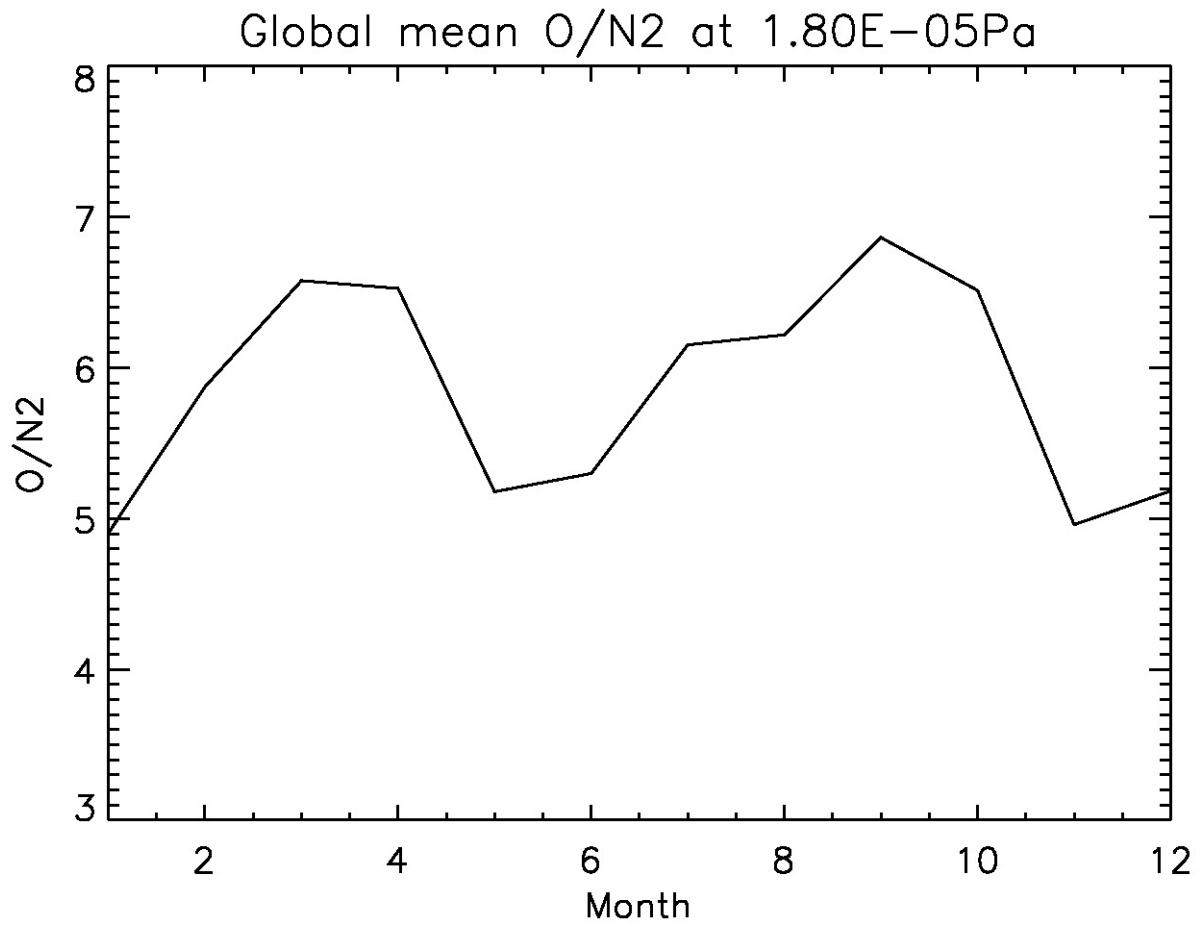
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**Figure 1: Compositional, Thermal, and Wind Structures from WACCM**  
*[Globally averaged number densities of constituents (upper and middle panel) and zonal mean temperature, zonal wind and meridional wind (lower panel), all averaged over December, from the ground to the upper thermosphere from a WACCM simulation.]*



**Figure 2: Short-term Variability from WACCM**  
*[3-hourly output of meridional wind over December from the ground to the upper thermosphere from a simulation using the extended WACCM.]*



***Figure 3: Semi-annual variation of thermospheric  $O/N_2$  from WACCM.  
[This is the globally averaged  $O/N_2$  at  $1.8 \times 10^{-5}$  Pa (about 250 km) from WACCM  
simulation of one model year. The semi-annual variation of  $O/N_2$   
is self-consistently resolved.]***